ROLLED-RIBBON® TECHNOLOGY

THE BEST HIGH-POWER HIGH-CAPACITY
LI-ION BATTERIES

The Rolled-Ribbon® Advantage

November 1, 2016

Rolled-Ribbon
BATTERY COMPANY

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The Problem

Batteries are essential components in all manner of electrical and electronic systems and products used in consumer, automotive, marine, industrial, utility and military applications.

Li-ion batteries, first proposed in the 1970s and commercialized in the 1990s, have proven to be particularly good for a broad range of applications. They provide:

- High volumetric and gravimetric energy density (small size, light weight)
- High cycle life (greater than 2,000-10,000 cycles)
- Long calendar life (up to 20 years)
- High-power delivery (high C-rates)
- Rapid charging capabilities (less than one hour)
- High energy conversion efficiency (greater than 95%)
- Low self-discharge (less than 3% per month)
- Zero maintenance (“install it and forget it”)

Over the past 15 years, Li-ion batteries have gone from being “seldom heard of” to totaling taking over consumer electronics. Today, it would be very difficult to find any consumer electronic device (cell phone, laptop, tablet, digital camera, power tool, etc.) that is not powered by a Li-ion battery. They have displaced previous battery technologies in products and they have enabled whole new products that were impractical using previous battery technologies.

Consumer electronic devices use relatively low-power, low-capacity Li-ion batteries. The larger market for Li-ion, however, is for high-power, high-capacity batteries. The current state-of-the-art in Li-ion battery design, as articulated by Nelson, et al. [1], is based on conventional cylindrical, pouch and prismatic cells. But these cell package designs were created for relatively low-power, low-capacity battery systems and do not scale up well for high-power, high-capacity requirements. Notably, structural impedances and thermal resistances increase disproportionately at the cell and battery level, leading to poor power delivery, increased heat generation and thermal issues.

It is well-settled that effective thermal management is essential to Li-ion battery performance and safety. [2,3,4,5,6,7] Poor thermal management greatly foreshortens cell cycle and calendar life. It also increases the possibility of, and the severity of, safety events. For large battery systems, cell life has a direct and inverse relationship on a battery’s cost-of-ownership. This is true even when cell life exceeds a battery’s

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1. P. Nelson, K. Gallagher, I. Bloom and D. Dees, *“Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles”,* Second Edition, December 2012.
2. P. Nelson, K. Gallagher, I. Bloom and D. Dees, *“Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles”,* Second Edition, December 2012.
3. S. R. Alavi-Soltani, T. S. Ravgururajan and M. Rezac, *Proceedings of IMECE 2006*, American Society of Mechanical Engineers, p. 383 (2006).
4. P. Nelson, D. Dees, K. Amine and G. Henriksen, *Journal of Power Sources*, pp. 110, 349 (2002).
5. Todd M. Bandhauer, Srinivas Garimella and Thomas F. Fuller, *“A Critical Review of Thermal Issues in Lithium-Ion Batteries”*, *Journal of the Electrochemical Society*, 158(3) pp. R1-R25 (2011).
6. K. Smith, T. Markel, G. Kim and A. Pesaran, *“Design of Electric Drive Vehicle Batteries for Long Life and Low Cost”*, IEEE 2010 Workshop on Accelerated Stress Testing and Reliability, October 6-8, 2010, NRE/PR-5400-48933.
7. K. Lee, K. Smith and G. Kim, *“A Three-Dimensional Thermal-Electrochemical Coupled Model for Spirally Wound Large-Format Lithium-ion Batteries”*, Space Power Workshop, April 18, 2011, NREL/PR-5400-51151.

first-use in that cells can be repurposed for subsequent uses, thereby creating or increasing end-of-life (EOL) value. Beyond the foregoing, long cell life also has virtuous sustainability advantages through reduced environmental impact that indirectly affects real product costs.

Thermal management impacts the cost, size, weight and energy efficiency of batteries. The relative impact, in no small measure, turns on thermal and other properties of the cells that are being managed. Some cell designs produce more heat per unit of work performed, requiring more complex and higher capacity cooling systems to extract the heat. Some cell designs pose greater challenges in configuring thermal management solutions. These and other factors lead to thermal management systems that are larger, heavier, more expensive and/or less energy efficient.

Notwithstanding the foregoing, most battery research has been focused on finding materials to improve the specific energy and power of batteries. Relatively little has been done to address thermal issues, in general, and to improve the thermal properties of cell package designs, in particular. But high-power, high-capacity systems are not limited by the energy density of electrochemistry. They are limited by thermal challenges.

Bandhauer, et al., in their study of Li-ion battery thermal issues published in 2011 [8], correctly observed and summarized that the essential thermal problem with current batteries is poor thermal conductivity in cells that create large thermal resistance between the heat generation sources (principally electrodes) and the cooling fluids. Further, they noted that this problem was more pronounced in multi-cell battery packs.

From the foregoing as well as other studies within the industry, it is manifestly clear that a new, more thermally effective and efficient, Li-ion cell package design is necessary to address the needs of high-power, high-capacity Li-ion battery systems.

The Solution

The Rolled-Ribbon Battery Company anticipated that there would be an enormous potential market for high-power, high-capacity Li-ion batteries, but it also recognized that conventional cell package designs would ultimately limit the ability of Li-ion to reach its full market potential. Accordingly, the Rolled-Ribbon Battery Company focused its research and development efforts on developing an alternative cell package design that could unleash Li-ion's potential for high-power, high-capacity batteries. At the end of the day, batteries can never be any better than their underlying cells. Ultimately, battery designs are framed and constrained, for better or worse, by the foundations laid by their underlying cell package designs.

In 2004, the Rolled-Ribbon Battery Company applied for, and received, a series of grants from the National Science Foundation (NSF) to develop a new and innovative cell package technology that would specifically address the thermal and other technical challenges associated with high-power, high-capacity Li-ion cells and batteries. This led to the development of Rolled-Ribbon® (RR) technology, which includes the unique disc-shaped RR cell package and cell stack designs that are shown in Figure 1 and Figure 2 below.

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[8] Todd M. Bandhauer, Srinivas Garimella and Thomas F. Fuller, *"A Critical Review of Thermal Issues in Lithium-Ion Batteries"*, *Journal of the Electrochemical Society*, 158(3) pp. R23 (2011).

Figure 1 – Rolled-Ribbon Cells

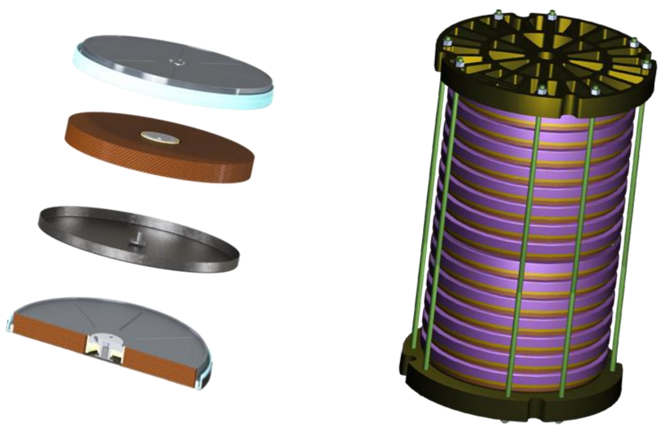

Figure 2 – Rolled-Ribbon Cell and Cell Stack

The first RR cells were demonstrated in 2007. Rolled-Ribbon Battery Company developed a RR battery to replace the battery in a Toyota Prius Hybrid vehicle. The resulting battery was 80% smaller than the stock Toyota Prius battery. It was also substantially lighter and performed better. In side-by-side road tests, the Toyota Prius with the RR battery had substantially better power delivery than the stock Toyota Prius battery. The RR battery, without any external thermal management, performed better than the Toyota Prius, with its stock external thermal management system.

The patented RR cells are fundamentally different than conventional cells, as can be seen Figure 3 below. Their unique properties enable the design of simple, efficient, long lasting, low-cost, high-power, high-capacity cells and batteries that are rugged and durable and that require minimal thermal management. Benchmark tests between RR and conventional cells, using identical electrochemical formulations, have shown that RR cells provide vastly superior thermal performance while reducing DC Internal Resistance (DCIR) by more than 50%, reducing AC Impedance (ACZ) by more than 75% and increasing cycle life by up to 400%. RR technology is independent of Li-ion electrochemistry, so it can be used with present and future advanced Li-ion electrochemical formulations.

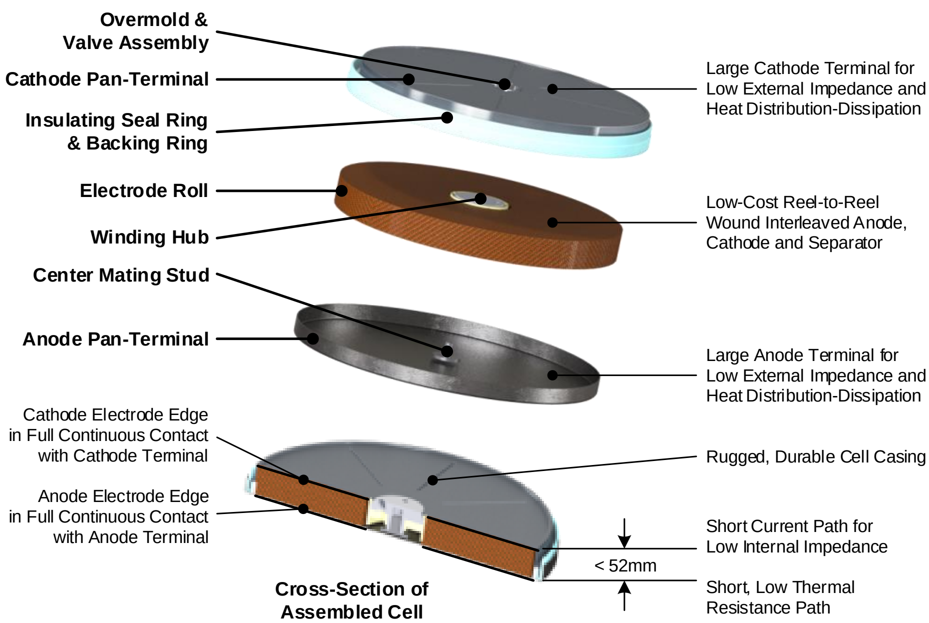

Figure 3 – Exploded View of Rolled-Ribbon Cell and Cross-Section of Assembled Cell

RR cells, as shown in the exploded view in Figure 3 above, are constructed by interleaving and winding long, narrow strips (ribbons) of anode, cathode and separator materials on a hub, producing an electrode roll (hence the term “Rolled-Ribbon”). Winding electrodes is one of the oldest, lowest-cost and most reliable methods for producing cells. The electrode roll is compressed between two pans that are separated by an insulating seal ring and the cell assembly is crimp-sealed. The top pan includes a safety pressure release valve (to vent excess pressure should it build up inside a cell under fault conditions). One pan serves as the cell’s anode terminal and the other serves as its cathode terminal. The electrodes in the electrode roll are perpendicular to the flat surfaces of the pans. The entire edge of the anode electrode is in direct contact with the anode pan and the cathode electrode is in direct contact with the cathode pan. There are no welded tabs of any kind.

RR battery modules are created by simply stacking RR cells, anode-to-cathode, on top of each other and compressing them between two end-caps, as illustrated in the RR Cell Stack shown in Figure 2 above. The large cell terminal surfaces provide low impedance cell-to-cell interconnection without bus bars, plates, tabs or welds of any kind. They also provide large thermal exchange surfaces with low thermal resistance. Finally, the RR battery module structure not only improves performance and reduces cost, size and weight, but it makes cell-level battery module repair and cell repurposing infinitely possible and trivial.

The performance advantage of RR is easily understood by comparing and contrasting the RR cell structure to conventional cell structures.

The RR cell structure is shown in Figure 4 below.

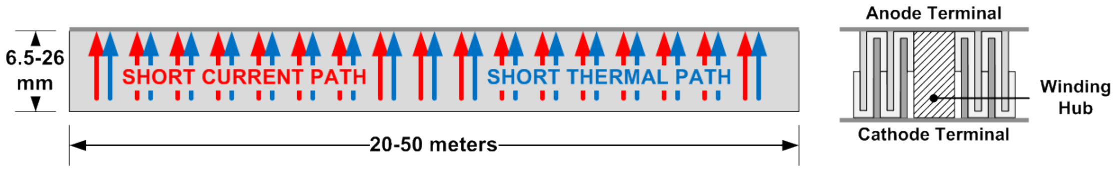

Figure 4 – Rolled-Ribbon Cell Structure

RR cells have narrow electrodes (typically 13-26 mm) whose edges are in direct contact across their entire length (typically 20-50 meters) with their associated cell terminal. From an electrical perspective, this creates a very short, low impedance path to the cell terminal. From a thermal perspective, this creates a very short path with very low thermal resistance to the very large cell terminal. This is because heat travels along the electrode foil rather than through multiple layers of electrode material, foil and separator. Nelson, et al., calculated that the thermal resistance along an electrode foil is on the order of fifty times lower than crossing electrode layers. [9] Through experimentation, Drake, et al., estimated the difference in thermal resistance to be on the order of 100 to 200 times. [10] If an internal short develops, by whatever means, the low thermal resistance of the RR cell will enable it to rapidly diffuse and dissipate the heat, minimizing the impact of a safety event and its ability to propagate.

The cell structure for conventional cylindrical, pouch and prismatic wound-tabbed cells is illustrated in Figure 5 below.

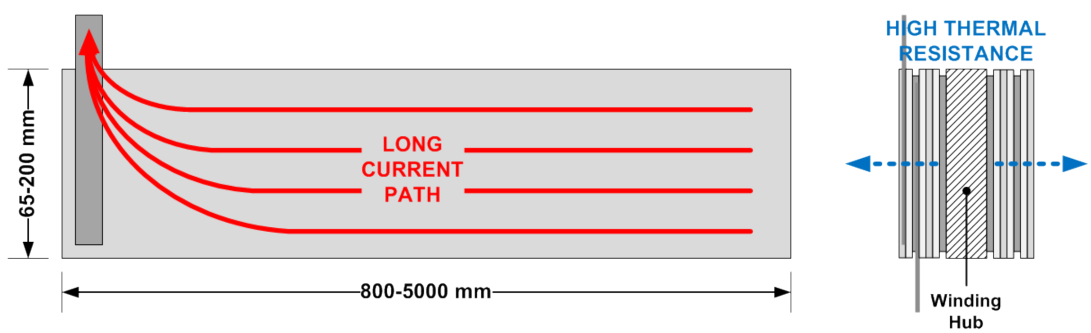

Figure 5 – Conventional Wound-Tabbed Cell Structure

These cells have long current paths (typically 800-5000 mm). This results in much higher impedance. Further, the heat generated from this impedance will not be uniformly distributed across the electrode. There will be much more current flowing as you approach the tab on the left-side than on the right-side, so there will be much more heat generated on the left than the right. Next, you have very poor thermal properties. Heat generated at the core must travel along a long longitudinal path of electrode foil through the highest heat portion of the electrode or overcome high thermal resistance through layers of electrode, including the highest heat portion of the electrode. This causes hotspots and thermal gradients that accelerate aging and can lead to safety events. If an internal short develops, by whatever

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[9] P. Nelson, K. Gallagher, I. Bloom and D. Dees, *"Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles",* Second Edition, December 2012, p. 45.

[10] S. Drake, M. Martin, M. Robinson, A. Jain, D. Wetz, J. Ostanek, S. Miller and J. Heinzel, *"Experimental Thermal Characterization of Various High Power Cylindrical Lithium Ion Energy Storage Devices"*.

means, the poor thermal properties will exacerbate the problem because there is limited ability to diffuse and extract heat.

The cell structure for conventional pouch and prismatic stacked-tabbed cells is shown in Figure 6 below.

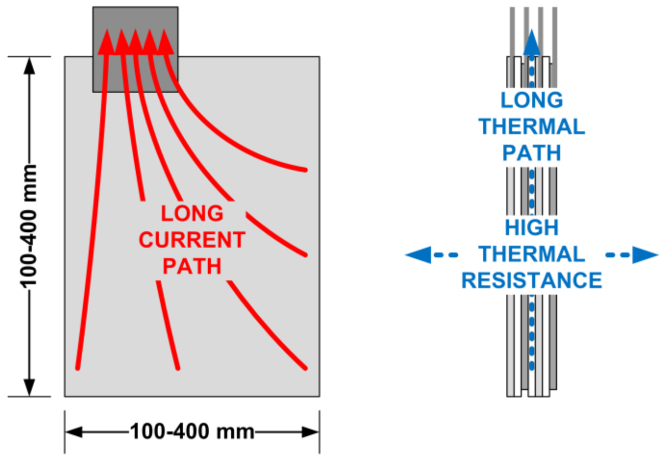

Figure 6 – Conventional Stacked-Tabbed Cell Structure

These cells have long current paths (typically 100-400 mm). This results in higher impedance. As with wound-tabbed cells, the heat generated from this impedance will not be uniformly distributed across the electrodes. There will be more current flowing as you approach the tab on the top than on the bottom, so there will be more heat generated on the top than the bottom. As with the wound-tabbed cells, you have poor thermal properties. Heat generated in the inner layers must travel along longitudinal paths of the electrode foils through the highest heat portion of the electrode or overcome the high thermal resistance through layers of electrodes. This causes hotspots and thermal gradients that accelerate aging and can lead to safety events. If an internal short develops, by whatever means, the poor thermal properties will exacerbate the problem because there is limited ability to diffuse and extract heat.

In an independent study of cell thermal properties [11], NREL modeled electrical and thermal performance of various cell designs and geometries, including various cylindrical designs. They concluded that flat (pancake-like) cells, like RR, would provide the best heat dissipation. They also concluded that these would be preferable relative to all cylindrical geometries. Accordingly, the RR design is theoretically favored by modeling.

The Rolled-Ribbon Battery Company has conducted a number of tests that support the theoretical models. A few of these are presented and described below.

In one test, the Rolled-Ribbon Battery Company compared the temperature increase for full cell discharges at various C-rates between a 1Ah 18650 cylindrical cell and a 12Ah RR cell, both using an identical nano c/LFP power formulation. The results are shown in Figure 7 below. As can be seen, for any

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[11] Lee, K. J.; Smith, K.; Pesaran, A.; Kim, G. H. *"Three Dimensional Thermal-, Electrical-, and Electrochemical-Coupled Model for Cylindrical Wound Large Format Lithium-ion Batteries"*, Journal of Power Sources, Vol. 241, 1 November 2013, pp. 20-32. (2013) NREL Report No. JA-5400-57328

given C-rate, the temperature increase for the RR cell is always lower than the 18650 cylindrical cell. As the C-rate increases, the RR thermal advantage increases.

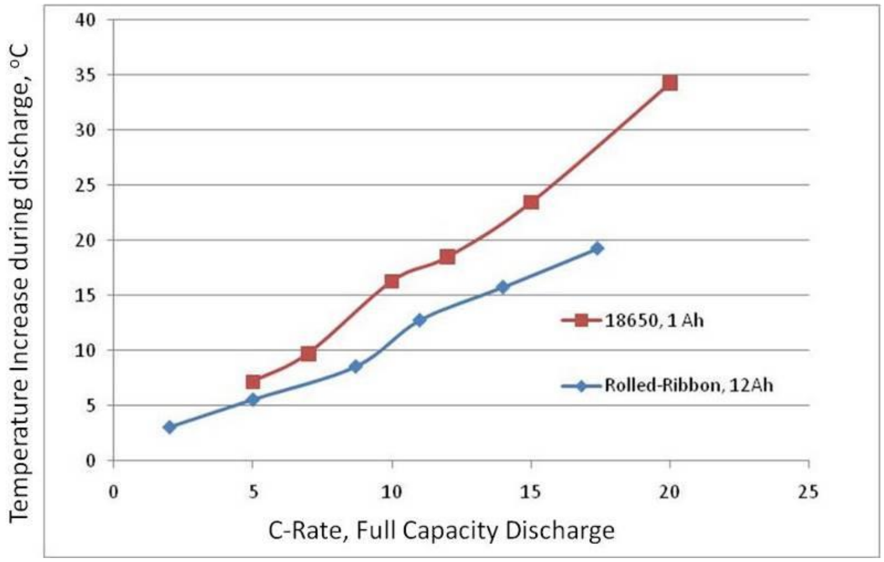


Figure 7 - Temperature Increase vs. C-Rate Discharge
1Ah 18650 Cylindrical and 12Ah RR Cells with Identical Nano c/LFP Formulations

But the thermal advantage is even greater than what the chart in Figure 7 above shows. The indicated temperatures are at the surface of the respective cell packages. What really matters is the temperature of electrochemistry inside the cells. Studies performed and models developed by the University of Texas at Arlington suggest that the internal temperatures for cylindrical cells could 20°C hotter or more than their surface temperatures, while internal temperatures for RR cells might be only be 5-10°C hotter. This is simply because RR cells have much lower thermal resistance between their internal electrodes and their cell packages.

The superior thermal properties of RR cells provide very stable cell performance, enhancing cycle life. Figure 8 below shows capacity and DCIR @ 50% DOD versus cycle for a 2000-cycle formulation of c/LFP. As can be seen, after 2500 C-rate cycles, cell capacity is within 12% of its initial capacity and DCIR has increased less than 10%. Conventional cells would have changed by 20% or more at this point, reaching end of life. This RR cell will probably not reach end of life until 4000 cycles or so – providing more than twice its rated cycle life!

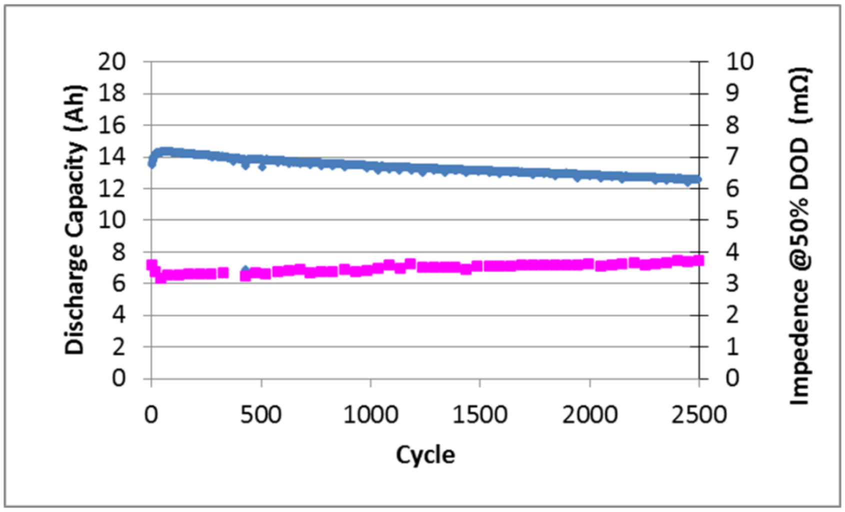


Figure 8 - Rolled-Ribbon Cycle Life Test, 2000-Cycle Formulation of c/LFP (12% capacity loss, 10% DCIR growth, estimated EOL=4000+ cycles)

For NSWC-Crane, the Rolled-Ribbon Battery Company recently conducted tests relative to a Directed Energy Weapon (DEW) requirement for 7.5kW power pulses of 2.5 minutes in duration. For comparison purposes, tests were conducted using 12Ah wound prismatic cells with aluminum casings and 14Ah RR cells. Both cell types used identical electrochemical formulations, so all differences in test results are strictly a result of differences in cell package design. Figure 9 shows the DCIR vs. Depth-of-Discharge (DOD) for the two cell types. As can be seen, RR reduced the DCIR by more than 50%. It also reduced the ACZ by 75%. Figure 10 shows the HPPC test results for the two cell types. The wound prismatic cells struggled to complete one 2.5 minute pulse per charge at the reduced discharge power rate of 185 watts. They were only able to deliver 24% of their rated capacity and their temperature rose by 28.5°C. The RR cells, on the other hand, sustained 7.5 minute pulses per charge at the full discharge power rate of 250 watts. They were able to deliver 70% of their rated capacity and their temperature only rose by 5°C! A battery with 15-series 2-parallel 14Ah RR cells could easily meet their volume and weight requirements. At 7.5kW for 7.5 minutes, the test results show that the RR battery could exceed the DEW battery requirements by 200%.

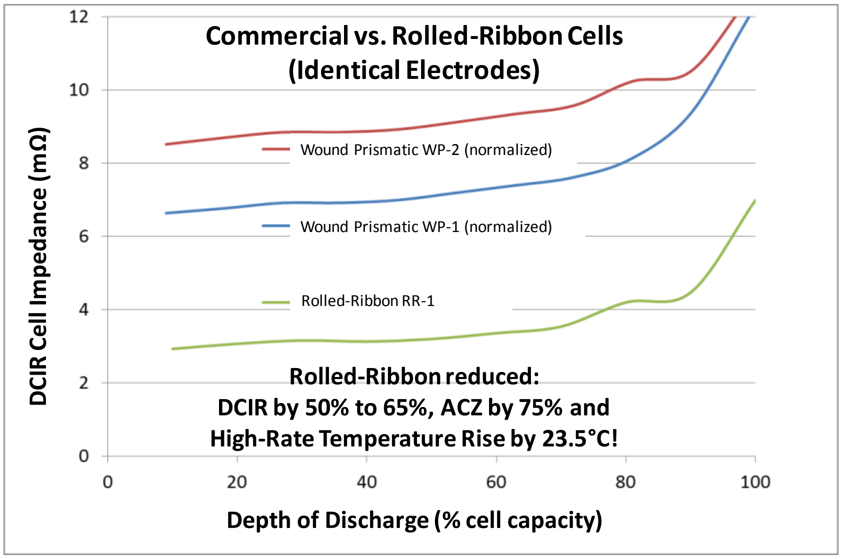
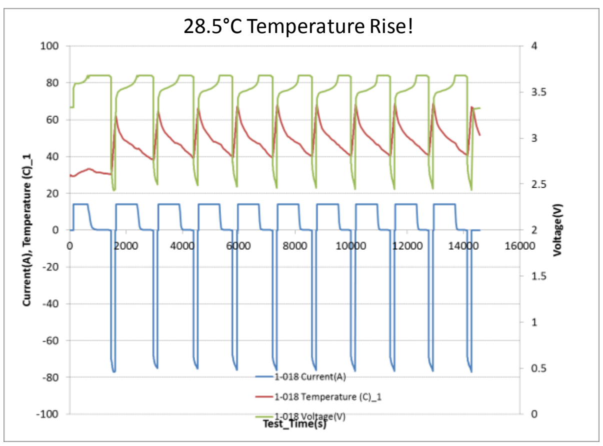
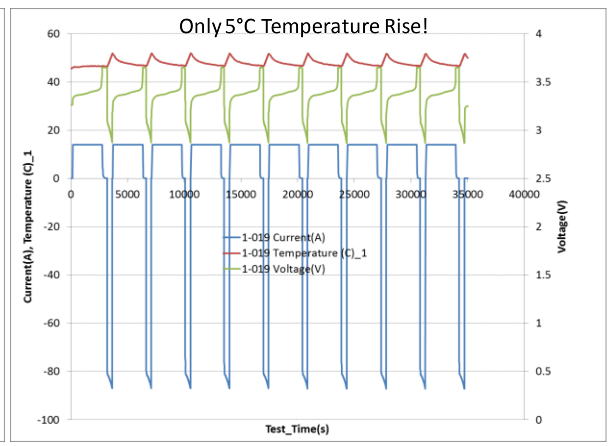


Figure 9 - Comparison of Commercial Wound Prismatic to Rolled-Ribbon DCIR vs. Depth-Of-Discharge



WP-2, 13.5Ah@1C, HPPC, HRC, 185W-2.5min pulse (24% discharge in 2.5min) (Commercial Cell)



RR-2, 136x13mm, 14.5Ah, HPPC, HRC, 250W-7.5min pulse (70% discharge in 7.5min) (7.5kW, 15s2p)

Figure 10 - Comparison Commercial Wound Prismatic to Rolled-Ribbon Voltage, Current & Temperature for High-Rate HPPC Test

But the profound thermal benefits of RR technology extend beyond the internal workings of the cells. They provide virtuous properties to battery designs as well. To demonstrate this, two test results are shown below.

In the first test, an adiabatic test was performed on a 10Ah cell with electrodes rated for sub-3C discharge. To generate a lot of internal heat, the cell was 100% continuously discharged at a 10C rate. The results are shown in Figure 11 below. As can be seen, the cell temperature rose by approximately 30°C during the discharge, but the temperature gradient from the center of the cell to the edge of the cell was less than 1°C, indicating the low thermal resistance of the cell package.

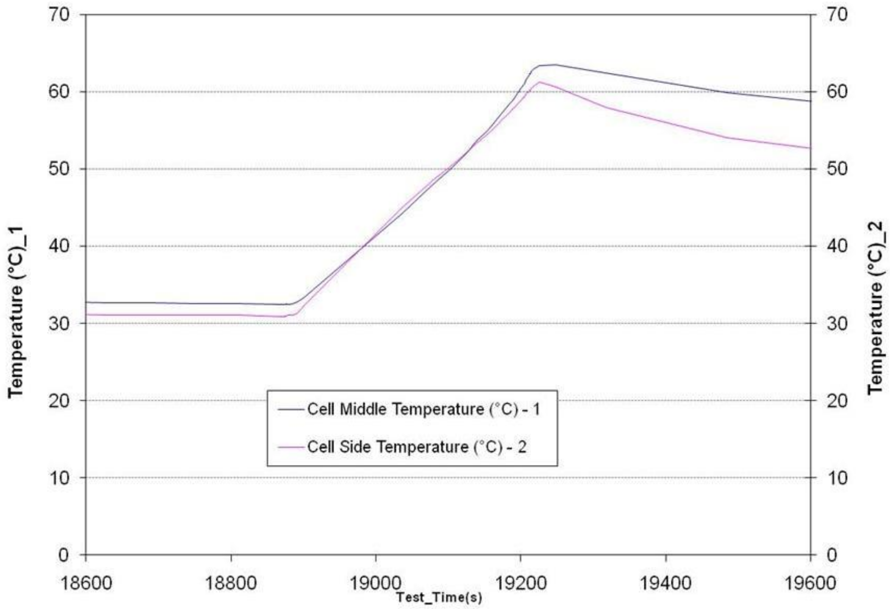


Figure 11 - Cell Package Thermal Properties
Adiabatic Cell Test, 10Ah Cell, Sub-3C Discharge Rated, 100% Discharge @ 10C

In the second test, a 12-cell stack was created with 7Ah cells with electrodes rated for sub-3C discharge. To generate a lot of internal heat, the cell stack was 100% continuously discharged at an 8C rate. The results are shown in Figure 12 below. As can be seen, the temperature rose by approximately 12°C during the discharge, but the temperature gradient from the edge of the end cells to the center cell was less than 2°C, indicating the low cell-to-cell thermal resistance of the cell stack.

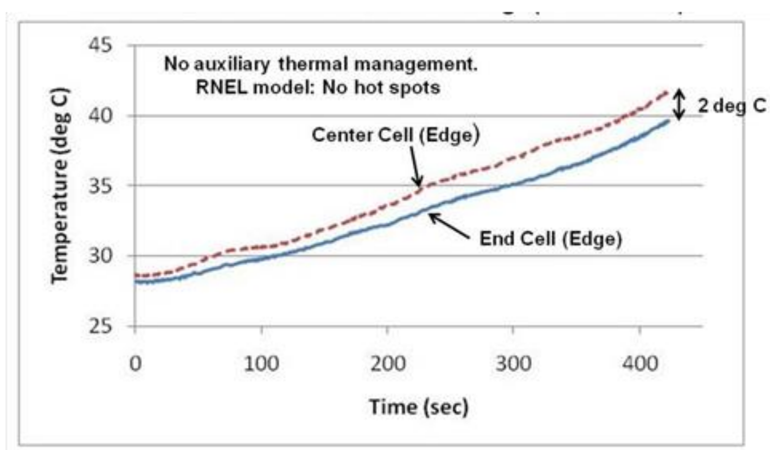


Figure 12 – Cell Stack Thermal Properties
12-Cell Stack, 7Ah Cells, Sub-3C Discharge Rated, 100% Discharge @ 8C

There are three important principles of thermal management that make RR technology essential and compelling:

1. Minimize heat generation. The best way to minimize thermal issues and the design challenges that they create is to minimize the generation of heat in the first place. Quite simply, if you

generate less heat, you have less heat to manage. In the case of batteries, this turns on reducing impedances in the electrical path between power sources and electrical loads. Thus, it begins with cell electrodes, but extends through cell tabs, cell terminals, cell interconnections, bus bars, battery terminals and the like.

2. Minimize thermal resistance. Thermal resistance is an expression of the velocity (rate) at which heat can be conducted between a heat generating source and a cooling heat sink. Therefore, thermal resistance should be minimized to maximize the rate at which heat can be extracted from a device. In the case of batteries, this turns on reducing thermal resistances between heat generating sources (cell electrodes, cell tabs, cell terminals, cell interconnections, bus bars, battery terminals and the like) and cooling heat sinks.
3. Thermal resistance is additive. The thermal resistance of a path is the sum of all thermal resistances in the path. Accordingly, the thermal resistance of a path is always higher (often much higher) than the highest thermal resistance in the path. Once a component of high thermal resistance is allowed in a thermal path, it can never be neutralized.

RR cell manufacturing is compatible with established Li-ion cylindrical cell manufacturing methods. The frontend manufacturing processes are identical. (i.e., electrochemical formulation, mixing, electrode coating, electrode calendering and electrode/separator slitting) The backend processes are quite similar, but different. (i.e., electrode/separator winding, electrolyte filling and crimp sealing)

Key Takeaways

The key “takeaways” about RR cell designs are:

- Simple, efficient cell design and assembly (few parts, few processes, no welded tabs)
- Very low structural impedance (power delivery, heat generation, energy efficiency)
- Unparalleled thermal properties (thermal resistance, gradients, heat distribution/dissipation)
- Compatible with most existing Li-ion cell manufacturing processes
- Reliable, low-cost reel-to-reel electrode winding
- Configurable for diverse cell geometries (disk diameters and heights)
- Li-ion chemistry independent (use present and future electrochemical formulations)

The key “takeaways” about RR battery designs are:

- Simple, efficient battery design and assembly (direct cell-to-cell stacking/interconnection, few parts, few processes, no bus bars/tabs/welds)
- Very low structural impedance (power delivery, heat generation, energy efficiency)
- Unparalleled thermal properties (thermal resistance, gradients, heat distribution/dissipation)
- Cell-level repair and cell repurposing are infinitely possible and trivial

RR cells represent a near ideal solution for high-power, high-capacity battery systems. It uses the very same mechanisms to simultaneously reduce electrical impedances (reducing heat generation) and thermal resistance (increasing heat distribution, dissipation and extraction). And unlike conventional cell designs, these mechanisms all scale with cell capacity.

RR is the only known cell package technology that can provide low thermal resistance all the way from the electrodes inside the cell to the battery cases and external thermal management systems.